Life Cycle Systems Engineering Approach to NASA's 2nd Generation Reusable Launch Vehicle

By

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ABSTRACT

The overall goal of the 2nd Generation RLV Program is to substantially reduce technical and business risks associated with developing a new class of reusable launch vehicles. NASA's specific goals are to improve the safety of a 2nd-generation system by 2 orders of magnitude — equivalent to a crew risk of 1-in-10,000 missions — and decrease the cost tenfold, to approximately $1,000 per pound of payload launched.

Architecture definition is being conducted in parallel with the maturating of key technologies specifically identified to improve safety and reliability, while reducing operational costs. An architecture broadly includes an Earth-to-orbit reusable launch vehicle, on-orbit transfer vehicles and upper stages, mission planning, ground and flight operations, and support infrastructure, both on the ground and in orbit. The systems engineering approach ensures that the technologies developed — such as lightweight structures, long-life rocket engines, reliable crew escape, and robust thermal protection systems — will synergistically integrate into the optimum vehicle.

Given a candidate architecture that possesses credible physics/processes and realistic technology assumptions, the next set of analyses address the system's functionality across the spread of operational scenarios characterized by the design reference missions. The safety/reliability and cost/economics associated with operating the system will also be modeled and analyzed to answer the questions "How safe is it?" and "How much will it cost to acquire and operate?"

The systems engineering review process factors in comprehensive budget estimates, detailed project schedules, and business and performance plans, against the goals of safety, reliability, and cost, in addition to overall technical feasibility. This approach forms the basis for investment decisions in the 2nd Generation RLV Program's risk-reduction activities. Through this process, NASA will continually refine its specialized needs and identify where Defense and commercial requirements overlap those of civil missions.

1.0 Background

The U.S. Space Launch Initiative (SLI) is the central focus of the National Aeronautics and Space Administration's (NASA) Integrated Space Transportation Plan (ISTP), a comprehensive strategy for revolutionizing space transportation in the 21st century. The ISTP includes: (1) Space Shuttle Safety Upgrades, (2) near-term investments in 2nd Generation Reusable Launch Vehicles (RLV), and (3) long-term research for 3rd Generation RLVs and In-Space Transportation systems for future space exploration.

Building on 20 years of success with America's 1st Generation RLV— the Space Shuttle — the SLI defines the plan of action to design space transportation systems and develop advanced technologies for America's next-generation RLV. It addresses business risk reduction for 2nd Generation RLV development and technology risk reduction for NASA-unique systems (i.e., crew survival features), as well as enables potential Alternate Access to the International Space Station (ISS). Therefore, SLI is synonymous with the 2nd Generation RLV Program, which is managed by NASA's Marshall Space Flight Center (MSFC), with participation from NASA field Centers and aerospace contractors from coast to coast.

The 2nd Generation RLV Program's scope is not limited solely to the launch vehicle, but encompasses all elements of a space transportation system architecture, an integrated set of elements consisting of:

1. Earth-to-orbit launch vehicle
2. On-orbit transfer vehicles and upper stages
3. Mission planning
4. Ground and flight operations
5. Ground-based and on-orbit support infrastructure.

Figure 1 illustrates the interrelated nature of these elements, which function synergistically to accomplish the space transportation mission.

The 2nd Generation RLV Program is based on the philosophy that frequently launching NASA payloads on highly reliable reusable launch vehicles will significantly reduce the cost of space access, allowing the Agency to focus resources on its core missions of scientific discovery and exploration. [1] Overall goals are to substantially reduce technical and business risks associated with developing safe and reliable RLVs. NASA's specific goals are to:

- Improve safety — risk of crew loss — to less than 1-in-10,000 missions
- Decrease cost by a factor of 10 — to approximately $1,000 per pound of payload launched to low-Earth orbit (LEO).

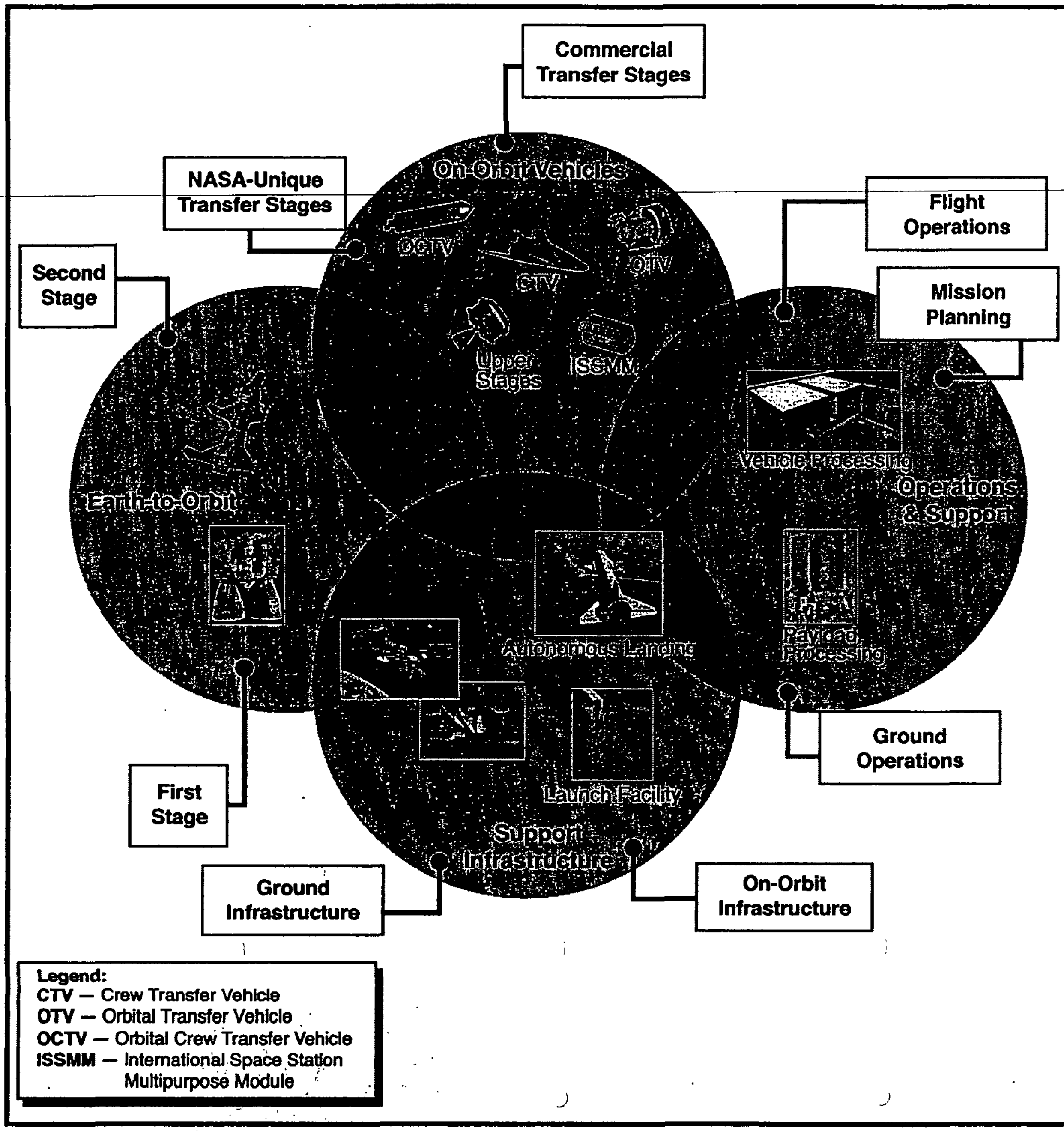

FIGURE 1. Space Transportation System elements.

Therefore, NASA is investing in strategic technology development in these areas for the express purpose of increasing safety and decreasing cost. While the space transportation architecture drives specific technology developmental objectives, the technologies ultimately enable the space transportation architecture.

The systems engineering and integration task consists of two distinct activities to be accomplished during the formulation phase covered by the 2nd Generation RLV Program:

1. Conduct System Studies — Define and comparatively evaluate candidate space transportation architectures, and develop and validate the associated systems requirements.
2. Coordinate Technology Developments — Maintain a technology portfolio to support evolving space transportation architecture(s).

Following is a description of the top-level systems engineering and integration processes developed to define a viable RLV architecture and mature the key technologies that will enable that architecture to meet Program objectives.

2.0 Systems Engineering Process Overview

The overall systems engineering and integration process is illustrated in Figure 5. System definition begins with communication with customers and stakeholders. The Program solicits customer and stakeholder needs and wants, and provides space transportation system capabilities and costs as feedback. The systems definition activity quantifies customer needs and wants in terms of Level 1 Program Requirements and design reference missions (DRM), and quantifies system capabilities and costs in terms of mission-level figures of merit (FOM) — measures to which customers and stakeholders can relate. This activity also articulates the space transportation system's intended usage scenario in a Operations Concept Document for the architecture.

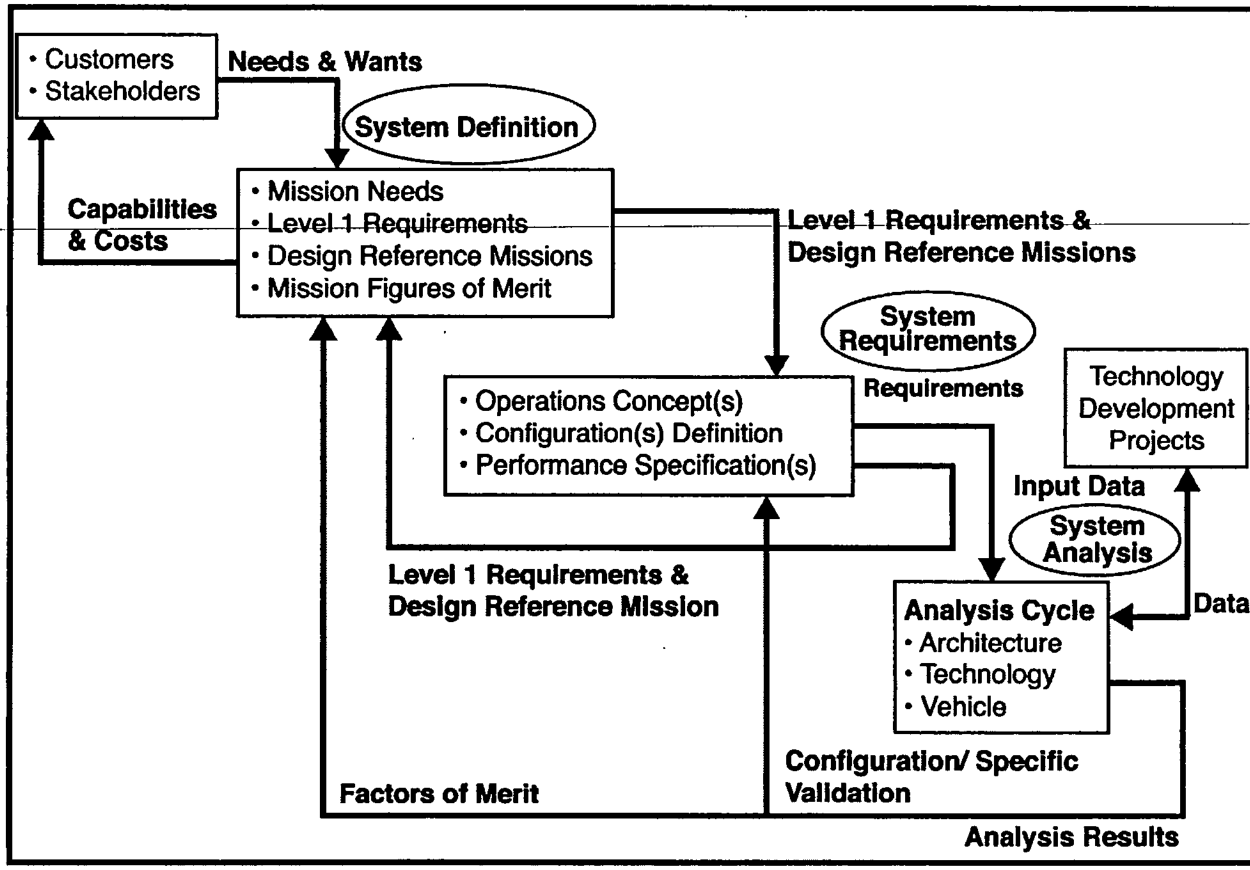

FIGURE 2. Systems engineering and integration process.

The systems requirements activity takes the system definition and develops a requirements allocation and flow-down for the space transportation system. This is the key integrating mechanism for the Program. It includes requirements synthesis with the individual projects within the advanced technology portfolio.

Given a requirements basis for a space transportation system, the systems analysis activity validates the requirements, using a design analysis cycle (DAC) process. The feedback provided indicates which requirements are valid and which are not; this information, in turn, influences the technology portfolio or may even affect Level 1 Requirements. The output of a design analysis cycle will also include the mission-level figures of merit in support of the system definition activity. Over time, successive cycles will result in convergence to the optimal space transportation system architecture, as illustrated in Figure 6.

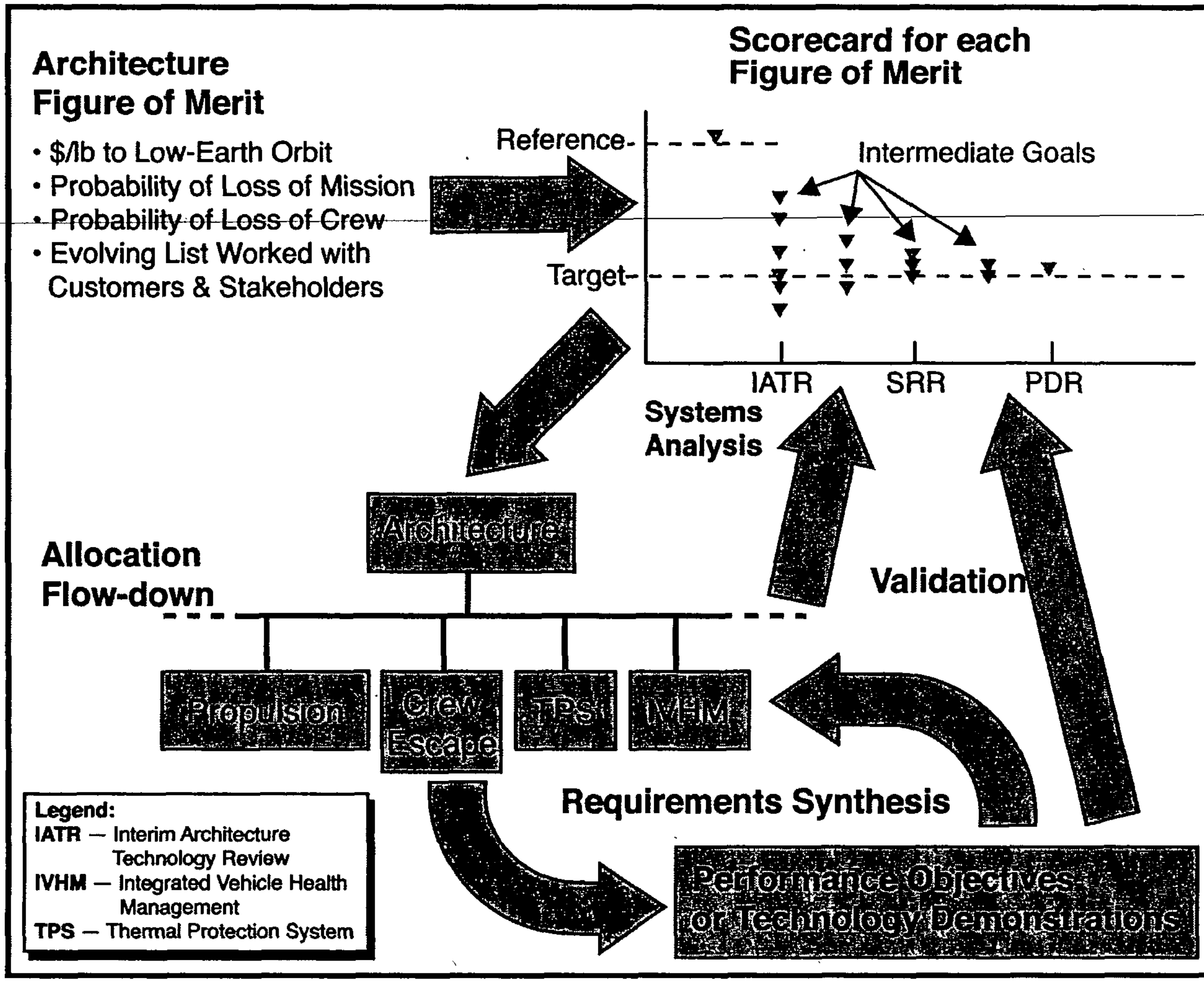

FIGURE 3. Convergence to the optimal Space Transportation System architecture.

3.0 Life Cycle Systems Engineering Process

Reliability, maintainability, and supportability engineering are closely interrelated design support disciplines that provide essential systems analysis capability for reusable systems requiring high reliability, high availability, and low operational cost. Each RMS engineering discipline has been practiced in industry and within the Department of Defense for decades following standard methodologies. In the 2nd Generation RLV Program these disciplines will be brought together similar to the way they have been practiced in industry and in other government agencies through an integrated RMS Process.

3.1 Overall Systems Analysis Process

Rigorous system analysis will indicate whether a system configuration, such as a candidate 2nd Generation RLV architecture, will satisfy requirements. The systems analysis process addresses five criteria, as shown in Figure 13:

1. Technical Viability
2. Technology Risk
3. Design Reference Missions
4. Safety/Reliability
5. Cost/Economics.

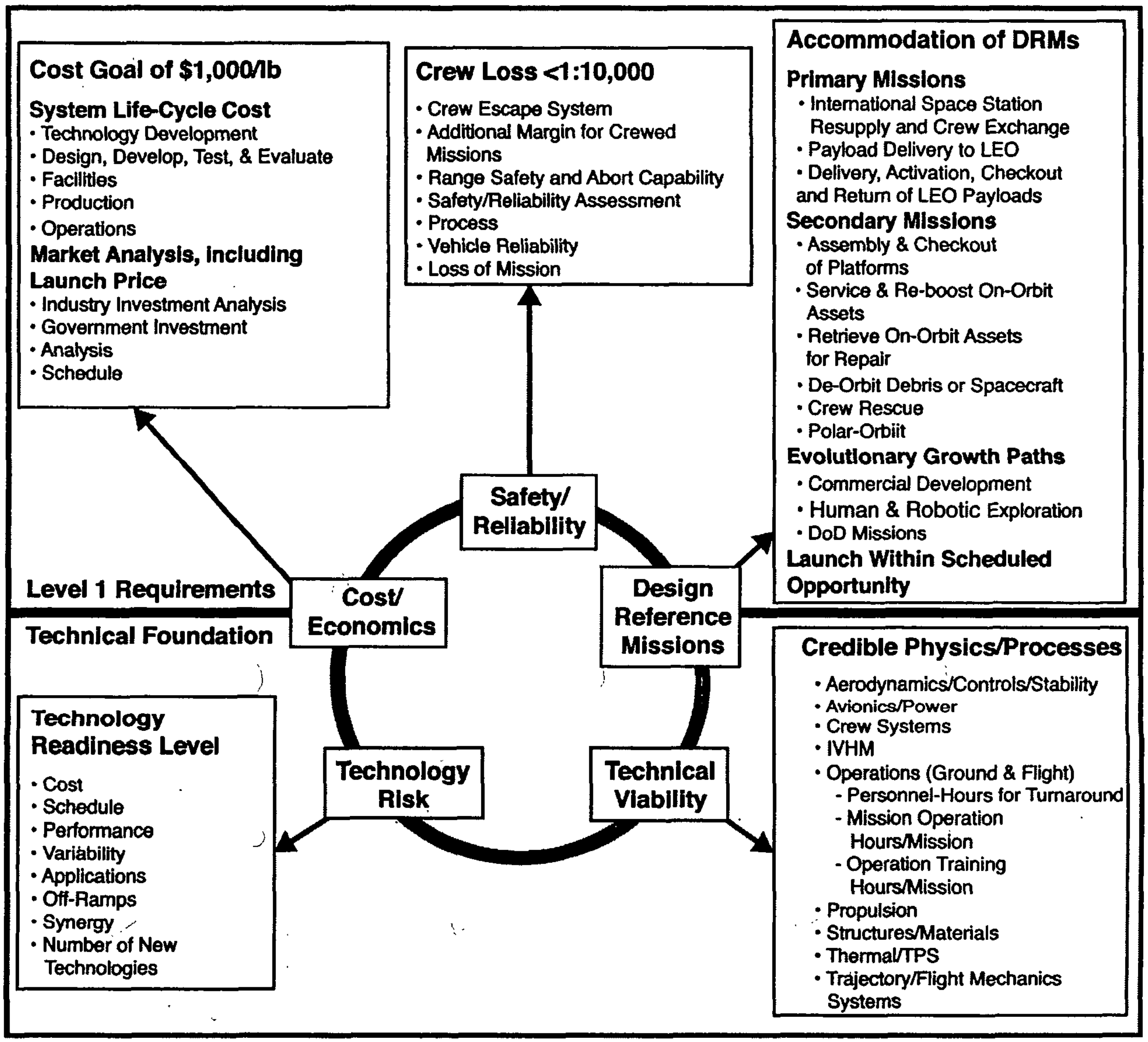

FIGURE 4. Criteria addressed by the systems analysis process.

Obviously, the first step in an architecture systems analysis is to model the system and determine whether it is credible from a physical science viewpoint.

This series of analyses will answer rudimentary questions such as "Can it reach orbit?" and "Will it survive the natural environment?"

Given that the configuration possesses credible physics and processes, systems analyses then focus on the technology readiness levels (TRL) of the various architecture elements. This series of analyses answers questions such as "Will the technology be ready in time?" and "What is the impact if the technology does not achieve performance goals?" The risk reduction technology projects and the mission requirements synthesis process provide data to reduce uncertainty in these analyses.

Given a candidate architecture that possesses credible physics/processes and realistic technology assumptions, the next set of analyses address the system's functionality across the spread of operational scenarios characterized by the design reference missions. The safety/reliability and cost/economics associated with operating the system will also be modeled and analyzed to answer the questions "How safe is it?" and "How much will it cost to acquire and operate?" The parameters included in the systems analysis process are depicted in Figure 13. Note also that the mission-level FOMs discussed in Section 2.1 are a subset of the systems analysis parameter set.

Repeating the systems analysis process for a large number of candidate architectures will validate the systems requirements. For example, if multiple architectures meet the 1-in-10,000 loss of crew requirement, it may be assumed this is a valid requirement that can be met by the 2nd Generation RLV when it is developed and operational. Conversely, if a requirement cannot be validated in that no candidate system architectures meet the requirement, the systems analysis process provides for requirements "push-back" to establish a valid requirement. Because the requirements are allocated across multiple architectural elements and based on assumed performance of various technologies, requirements "push-back" will lead to a requirement reallocation or relaxation for the architectural elements and/or the technologies, which prompts a new analysis.

One iteration of the systems analysis process is called a design analysis cycle. Over time, the character of DACs will evolve, growing in fidelity and precision; as it becomes available, test data resulting from risk reduction technology projects will be included in the DACs. In the near term, DACs will focus on the evaluation of a large number of candidate system architectures. Subsequently, the DACs' focus will shift toward greater detail on a smaller number of candidate architectures. Accordingly, the systems requirements validation will approach completion and the validation focus will shift to lower-tier requirements associated with architectural elements, subsystems, and components. Likewise, the mission-level FOMs will begin to stabilize and generally exhibit reduced variability over time. In this way, the systems analysis process: (1) validates systems requirements, and (2) determines the relative merit of various candidate systems architectures and technologies.

The Integrated RMS Process

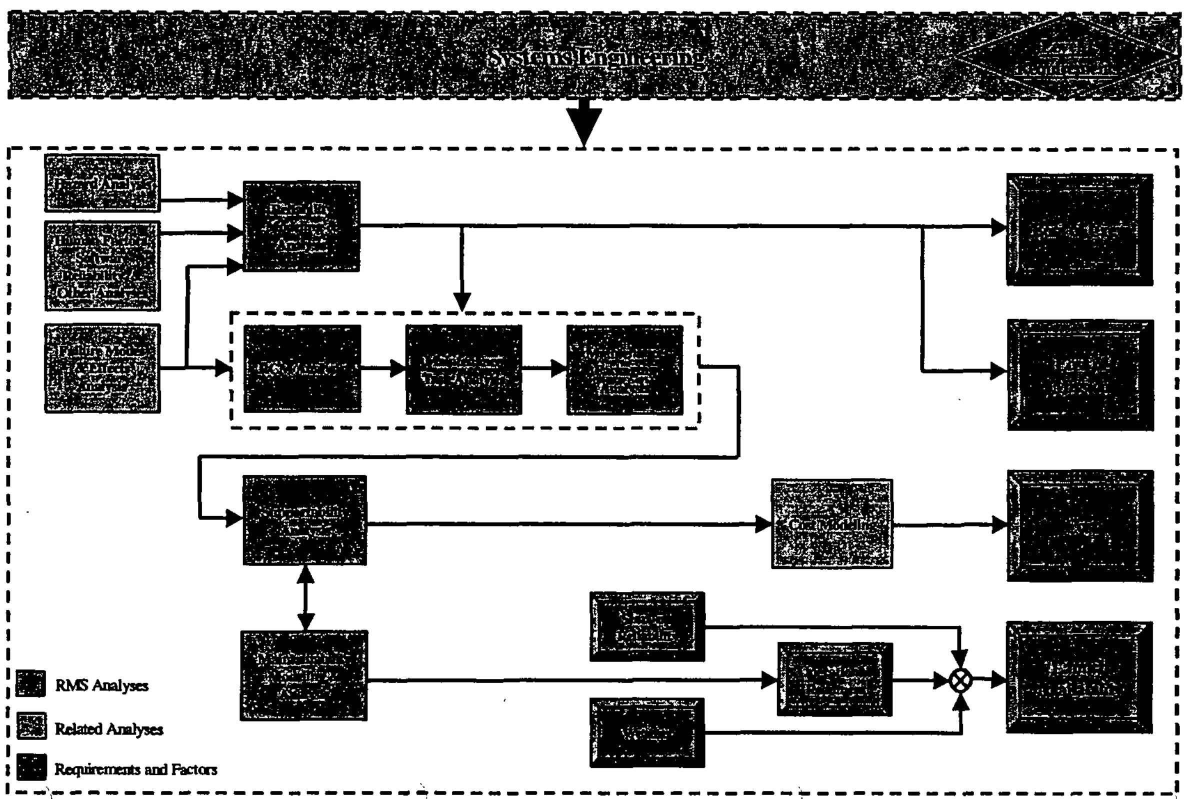

Figure 2

3.2 Reliability, Maintainability, and Supportability (RMS) Process

The RMS Process, illustrated in Figure 2, integrates the disciplines of reliability, maintainability, and supportability engineering through a specific sequencing of related RMS modeling and analysis tasks and through the flow of specific RMS data between the sequenced RMS tasks. The RMS Process also integrates the RMS modeling and analysis tasks, through the systems engineering process, with design engineering and with other engineering support disciplines such as cost and assurance.

The basic RMS Process begins with identification of failure states/events associated with the design, their severity, their causes, and their effects. This is done primarily through a Failure Modes and Effects Analysis (FMEA) of the design and is supported by Hazard Analyses and Human Factors Analyses. Next, reliability modeling and analysis develops reliability models of the failure modes/events and then arranges the individual models into a failure structure/logic model representing the ways in which system function may be lost. This logic model is executed analytically or through simulation to produce the primary output of the reliability modeling and analysis task: an estimation of system capability to meet reliability and safety figures of merit of PLOC, PLOV, PLOM, and PLOP. At the same time, parameters from reliability models along with certain FMEA data serve as input into reliability-centered maintenance (RCM) analysis. The RCM analysis takes this input and runs it through an established RCM logic flow to generate an inventory of maintenance significant items (MSI) and basic maintenance actions required to retain or restore MSI function at or to specified levels of reliability/safety. The inventory of MSI and basic maintenance actions serves as primary input into both the maintainability and supportability modeling and analyses tasks that are closely interrelated and performed concurrently.

Maintainability modeling and analysis begins with the development of a top-level maintenance event sequence model initiated during conceptual design. It is continually decomposed to lower levels of indenture with increasing definition of system architecture, of maintenance and support tasks, and of maintenance packaging schemes. Once complete it provides a definitive maintenance and support (e.g., ground processing) flow model. Maintainability models estimating elapsed time for individual and grouped maintenance actions/events are developed concurrently at each level of indenture in the maintenance event sequence model. A downtime analysis is performed when required by executing the maintenance event sequence model analytically or through simulation. The downtime analysis estimates the capability of the maintenance and support system to deliver a space flight system ready for integration or flight within specified time constraints. This output at the vehicle level is combined with estimates of the start-up reliability of the launch vehicle and with estimates of the probability of the launch vehicle architecture not exceeding day-of-launch environmental constraints to produce an estimate of the launch availability FOM for the launch vehicle architecture.

Supportability modeling and analysis begins primarily with the maintenance task analysis that is initiated for each maintenance action output of the RCM analysis. This analysis is a decomposition of each maintenance action into all necessary steps for successful completion. A supportability analysis is performed concurrently with and on the maintenance task analysis to determine the required resource loading (facilities, personnel, support equipment, parts, etc.) for each maintenance action. Following the maintenance task analysis and concurrent supportability analysis, the individual maintenance actions are grouped into packaged sets of tasks that most effectively and efficiently meet mission, reliability, and cost requirements. The final set of packaged maintenance actions are documented (e.g., Space Shuttle OMRSD) for use by maintenance engineering. The supportability analysis is updated to reflect the packaged tasks and the output is provided to cost analysis in the form of total support resources per cost-breakdown-structure to support estimates of recurring cost.

3.3 Tools, MODELS and Databases

The RMS process will require both existing and new tools, models, and databases. Existing tools may be used for certain RMS modeling and analysis tasks. However, new software tools will be needed for certain analyses (e.g., RCM analysis) and to integrate the set of RMS models and analyses. Existing models such as the Space Shuttle Quantitative Risk Assessment System (QRAS) may be used extensively for reliability modeling, but new system-level models will be required for some reliability analysis, downtime analysis, and supportability modeling and analysis. These needs will be identified and met primarily through the Advanced Engineering Environment (AEE) activities, which utilizes a data dictionary for the input and output variables required by the models and tools in the AEE. The 2GRLV-SEAEE-PLAN-001, Advanced Engineering Environment (AEE) Project Plan provides further detail on the AEE processes and activities. Among existing databases that may prove useful are the Problem Reporting and Corrective Action (PRACA) database and A new database, the Baseline Comparison System (BCS), is being developed that will attempt to collect applicable data from a number of existing Space Shuttle databases, including the PRACA database, and merge the data into one RMS database.

3.4 Products

The RMS process will provide a set of integrated RMS products over the life of the 2GRLV program. Table X, RMS Program Products and Schedule, shows these products relative to major program milestones. The primary purpose of these products is to provide objective analytical evidence at each program review that candidate space transportation architectures meet the Level 1 RMS-related Requirements.

	Program Review			
	IATR	SRR	SDR	PDR
Plans, Processes and Req.:				
2GRLV RMS Plan and processes	Draft	Baseline		
Contractor RMS plan and processes	Draft			

RMS inputs to System Req.	**Prelim.**			
Allocated RMS Req.	Prelim.	Updated		
FMEA Requirements/Guidelines Document		Prelim.	Baseline	
Probabilistic Risk Assessment (PRA) Plan	Prelim.	Baseline		
Architectural Development:				
Integrated Architectural and Technology Assessments (ISAT)	Initial Down select (Top-Level)	Final Down select (more detailed)		
Integrated Vehicle Perform. Assessments (VIPA)		VIPA Models Demonstration	Detailed System Eval.	Updated System Eval.
Architectural Concept Studies	Top-Level	Detailed System		
RMS/Related Modeling, Assessments, Predictions:				
Reliability Products:				
Quantitative Reliability Anal.	**Top-Level**	**Updated**	Updated	**Updated**
Inputs to FOM Probabilities	**Prelim.**	**Updated**	Updated	**Updated**
Probabilistic Risk Assessment (PRA)			**Subsystem PRA model**	**Detailed PRA model**
FMEA/CIL (S&MA)		Prelim.	Updated	Updated
Logic Tree Analysis	Top-Level	Prelim.	Updated	Updated
Maintainability Products:				
Reliability-Centered Maint.		**Top-Level**	Updated	**Updated**
Quantitative Maint. Analysis	**Top-Level**	**Updated**	Updated	**Updated**
Maint. Task/Item Identification	**Top-Level**	**Updated**	Updated	**Updated**
Supportability Analysis:				
Maintenance Task Analysis		**Top-Level**	Updated	**Updated**

	Program Review			
	IATR	SRR	SDR	PDR
Maintenance Packaging				Prelim.
Repair Level Analysis (RLA)		Top-Level	Updated	Updated
LRU/SRU Selection		**Top-Level**	Updated	**Updated**
Provisioning (Spares, Consumables) Analysis		Top-Level	Updated	Updated
Transport./Packaging Req.		Top-Level	Updated	Updated
RMS Manpower/Training req.		**Top-Level**	Updated	**Updated**
RMS Facility Req.		**Top-Level**	Updated	**Updated**
RMS Equipment & GSE Req.		**Top-Level**	Updated	**Updated**
RMS-Related Products:				
Operations Analysis		**Top-Level**	Updated	Updated
Safety Hazards Anal. (S&MA)		Top-Level	Updated	**Updated**
Fault Detection/Isolation/ Recovery (FDIR) Analysis				Prelim.
Commonality/Standardization		Top-Level	**Updated**	**Updated**
Inputs to Program Risk Mgmt.		**Prelim.**	Updated	**Updated**
Technical Data Org/Mgmt		Top-Level		Updated

Post-production support req.		Top-Level		Updated

Table X. RMS PROGRAM PRODUCTS AND SCHEDULE

4.0 Summary to be written as narrative

- TBD
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5.0 References to be added